REPORT DOCUMENTATION PAGE			AFRL-SR-AR-TR-02- 0266

Public reporting burden for this collection of information is estimated to average 1 hour per response, inc ... sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. ... t of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Se ... efferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Pa...

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 23 JUL 2002	3. REPORT TYPE AND DATES COVERED FINAL (01-APR-2001 TO 30-SEP-2001)

4. TITLE AND SUBTITLE WORKSHOP ON THE MODELING, ANALYSIS, AND MEASUREMENT OF FRICTION CONSTRAINTS IN GAS TURBINE COMPONENTS.	5. FUNDING NUMBERS F49620-01-1-0325
6. AUTHOR(S) JERRY H. GIFFIN	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CARNEGIE MELLON UNIVERSITY MECHANICAL ENGINEERING DEPARTMENT PITTSBURGH, PA 15213	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AIR FORCE OFFICE OF SCIENTIFIC RESEARCH 801 N. RANDOLPH STREET ARLINGTON, VA 22314	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An international workshop on improved mechanics with applications to gas turbines with held on the 3rd and 4th of June in conjunction with the ASME Turbo Expo 2001. The workshop was organized by Dr. J. H. Griffin, a professor at Carnegie Mellon University in Pittsburgh, and Dr. E. Ewins, a Professor at Imperial College I London. An announcement was distributed to potential participants, refer to appendix 1: announcement. The workshop was attended by both European and American experts for industry, universities and government agencies - see Appendix 2: List of participants. The purpose of the workshop was to coordinate a global research initiative in this area of contact mechanics.

20020909 115

14. SUBJECT TERMS	15. NUMBER OF PAGES 11
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

JUL 2 3

Final Report

Air Force Office of Scientific Research
Award Number: F49620-01-1-0325

Workshop on the Modeling, Analysis, and Measurement of Friction Constraints in Gas Turbine Components

NEW ORLEANS, 3-4 JUNE, 2001

Submitted to

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1. Introduction

An international workshop on improved contact mechanics with applications to gas turbines was held on the 3rd and 4th of June in conjunction with the ASME Turbo Expo 2001. The workshop was organized by Dr. J. H. Griffin, a Professor at Carnegie Mellon University in Pittsburgh, and Dr. E. Ewins, a Professor at Imperial College in London. An announcement was distributed to potential participants, refer to Appendix 1: Announcement. The workshop was attended by both European and American experts from industry, universities and government agencies – see Appendix 2: List of Participants. The purpose of the workshop was to coordinate a global research initiative in this area of contact mechanics.

2. Synopsis of Activities

2.1 Day 1 (June 3, 2001) Afternoon.

- 1300 start,introductions
  Start by posing the question (**Griffin**):
  "Is there any mileage in trying to develop an international collaboration on the shared problems of the GT industry related to contact mechanics?"
  Two specific areas identified – friction damping (design tools for platform dampers; roots; shrouds, other parts) and contact stresses (dovetail root stress analysis problems; fretting and fatigue and life prediction requirements).

  Explain overall plan for workshop (**Ewins**):
  Identify the problems and requirements faced by industry
  Review the state of the art of current techniques and identify gaps; lack of capabilities
  Share ideas for new approaches, or improvements to existing methods
  Draw up a plan of action to make progress at an international collaborative level, where that is appropriate

- 1340 General Electric talk part 1: **Weaver** (GE) on friction damping
  Almost all damping in GT airfoils is entirely frictional
  Highlights stiffness effect as well as damping in u/p dampers
  Discussion of what is mechanical damping, underplatform dampers
  Describes the experiences with BDAMPER. Cannot match both stiffness and damping features with same model
- 1410 GE talk part 2: **Farris** (Purdue) on contact stresses
  Probabilistics is a major aspect of the problem
  Looking at interaction of HCF and LCF as part of the project at Purdue

- 1450 Rolls Royce talk part 1: **Lee** (RR-UK)
  Need to note the importance of materials and fatigue topics (outside scope of workshop)
  RR talk part 2: **Kielb** (RR-US): general discussion of friction dampers

Shows comparison of BDAMPER vs HBMSTR

- Main Conclusion – Day 1: Can we identify "What is the Problem?" "What does industry want/need?" Two areas were identified as related and important: determining the local contact stresses, and secondly, determining friction damping.
  For both areas we reached some general conclusions:

  <u>General conclusions for both contact stress and friction damping. There is a need to have:</u>

  - An ability (i.e. tools which enable us) to predict vibratory response in order to determine HCF life:
  - Tools which enable us to perform these predictions that are based on an understanding of the physics of the relevant phenomena which are being considered;
  - Prediction tools which are robust (not sensitive to small uncertainties in input data) and readily adaptable as techniques/methods/understanding improve with time;
  - Prediction tools which are cost effective,
  - Prediction tools which require the simplest levels of input data (i.e. which do not require advanced skills of user)
  - Prediction tools which are integrated into the design process

  <u>Conclusions specifically for friction damping applications:</u>

  - Modelling and analysis methods for which errors from inadequate contact mechanics understanding/modelling result in peak response predictions for forced vibration that are less than 25%
    (This means that the damping effects from the contact mechanics must be modelled correctly (within 25%) and that the stiffness effects from the contact zone must be modelled with sufficiently accuracy that natural frequency shifts are predicted to within 2%.)
  - An ability to predict the variability from blade to blade and engine to engine.
  - An ability to predict changes of these response levels with time.
  - Modelling and analysis methods which are be applicable for:
    - Underplatform dampers
    - Shroud contact regions
    - Attachments such as roots

  <u>Conclusions specially for contact stress applications:</u>

It was difficult to come to grips with the contact mechanics problem and to separate the stress calculations from the fatigue predict part of the problem, partly because it is currently not feasible to substantiate the local stresses on the contact interface. However, after extensive discussions the following statement was agreed upon, "There is a need for modelling and analysis methods for which errors from inadequate contact mechanics understanding/modelling causes a variation in predicting the probability of failure that is less than a factor of 10."

2.2 Day 2 (June 4, 2001) : Morning Discussion

- 0900: Presentations by:

  - **Farris** – on some state of the art techniques for contact stress/fretting fatigue predictions

  - **Menq** – on some state of the art of friction damping prediction techniques

  - **Ewins** –on some state of the art methods for measuring friction damping in contact areas, and structures

Followed by Discussions and then 3 Breakout Sessions each tasked to compile a list of the current Capabilities and current Incapabilities relevant to the needs identified on Day 1.

- 1130: Breakout session

Three groups to review the state of the art: Capabilities and Incapabilities

Results of Breakout Sessions:

Group 1 List. (Nowell)

Capabilities

- Can predict frequency shift (in u/p dampers) to 10%
- Can predict forced response levels of u/p dampers to within 2-3x
- Design assuming wide range of friction chics
- Predict 2D surface tractions with reasonable computers
- Predict 3D tractions (stresses) with large computing power
- 'predict' (i.e. understand) behaviour of 2D damper post-test
- do comparative studies between different damper designs
- can predict interblade phase angles
- reconcile continuum mechanics and 1D kinematics model (i.e. predict 1D microslip 2 different ways given fixed inputs)
- don't use shrouds unless essential

Incapabilities

- CANNOT predict frequency shift for u/p dampers to 2%
- CANNOT predict u/p response levels to within 25%
- CANNOT predict friction damping for dovetails/firtrees
- CANNOT characterise contact stiffness
- CANNOT predict friction chic (and variation with time, wear,..)
- CANNOT predict coating life (service-induced corrosion/wear,..)
- Need better measurements of slip/stresses/strains in dovetails
- CANNOT make the link between dovetail stresses and life
- CANNOT predict the location of contact and nature of constraints in u/p dampers
- CANNOT assess how manufacturing tolerances affect damping
- NEED to reconcile kinematics and continuum models for 2-3D
- NEED to understand importance of asperity compliance
- NEED to understand the behaviour of shroud contact

Group 2. (Lee)
Current Capabilities/Incapabilities

Damping
Number of codes available with following features

- Essentially 1D and harmonic excitation
- Rely on tuning of input parameters to get good correlation with test
- Limited number of geometry types
- Coulomb based friction model – coarse approximation
- Time-invariant models (wear etc not included)
- Parameters not consistent between amplitude and frequency

Propose:
Standard set of industry-wide benchmarks
System level validation

Fretting Fatigue
Hybrid predictive techniques available
Quasi static: 2D slices

Group 3:

CAPABILITIES

- Steady stress predictions/contact stress (2D)
- Contact Kinematics (BDAMPER)
  - Sensitivities
- Damper effectiveness and frequency shifts in engine after calibrating model with spin pit tests

MISSING CAPABILITIES

- Quick, 2D contact analysis (steady stress)
- Effective 3D contact analysis
- Damper stiffness
- Theoretical model to predict contact stiffness, friction coefficient, other parameters.
- Separation of contact surfaces
- Lack of data on material behavior under vibratory stress and high steady stress (monolithic & single crystal).
- Lack of data and models for variation of contact parameters with time (hot hold time, takeoff/landing)
- Method for measuring local contact stress/strains, etc.

2.3 Day 2 (June 4, 2001) : Afternoon – Theme: New Ideas, Developments, Plans

Presentations by:

- 1400: **Smallwood** (Sandia) on measurements of joint damping in a special rig
- 1410: **Szwedowicz** (ABB) on studies of underplatform dampers. Useful review of the various schools to study (CMU, IFM, IC, Volvo)
- 1420: **Sanliturk** (ISTANBUL) review of current models; need to measure contact properties; need to generate a theoretical model for joint contacts; he mentions the relevance of how friction may affect rotor dynamics (rotor/stator rub)
- 1430: **Sinha** (PSU) reports on mistuned, friction damped assemblies under random vibration
- 1440: **Petrov** (ICL) reports on application to root damping, new NL analysis methods
- 1450: **Griffin** (CMU) reports on new tests on sample contact area

Closing Discussions on a Way Forward

- Discussed suggestions for Benchmarks: both numerical ones for inter prediction comparisons, and experimental ones, for comparing predictions against test data
- Invited ideas for projects to be worked up
- (PWA) suggested need to line up funding before planning projects; Univ. thought other way round appropriate in this fundamental topic.
- Several attempts to link the contact stress problems and the vibration (friction damper) ones. Inclination towards the desirability to do so, not least to seek a better understanding of the physics necessary to develop better prediction methods.
- Agreed to have a further meeting of specifically interested parties in ~ 3months time to revisit the question of what specific actions could be taken on an international scale.
- Agreed on areas of research that should have high priority. These are listed in the next section.

3. High Priority Research – Short And Long Term

The following topics were assessed as having the highest priority. There is no significance to their order.

- An effective 3D contact analysis. Short term.
- A theoretical model to predict the contact stiffness, friction coefficient and other parameters the determine the hysteresis loop in the damper and shroud. This is seen as a long term goal. A short term goal is to predict the damper's stiffness. Also, this theoretical model would provide an understanding of how these parameters may change with time because of wear, oxidation, etc. and could be applied to real surfaces with coatings, etc.
- New Experimental Capabilities
    - Develop methods for measuring local contact stress, strains etc.
    - Develop a set of fundamental benchmark experiments that characterize nonlinear joint behavior.

4. Post Script:

Mr. Paul Garbett from Seimens Westinghouse sent an email after the meeting with the following suggestion on how the high priority research goals should be summarized. His suggestion was:

- Develop more elaborate models (e.g. 3D) that are integrated with commonly used FEA codes and the turbine design system.
- Develop new measurement techniques for the key parameters (e.g. friction coefficient, damper stiffness etc.) that can be directly input into these models.
- Develop predictive tools that can reliably establish these parameters during the design phase.
- Develop a knowledge base for the influence of real world factors on these models and parameters (e.g. coating, tolerances, surface condition etc.).
- Develop standard benchmarks to validate entire system, verify accuracy of models and test new developments.

5. Website

A website was developed that documents the workshop. The presentations given at the workshop and the final report can be accessed and downloaded from the website. The website address is: **http://www.me.cmu.edu/faculty1/griffin/2001/cmw.htm**

Appendix 1: Announcement

An AFOSR and NAVAIR Sponsored Workshop – June 2001

Improved contact mechanics with applications to gas turbines

Background

The term "contact mechanics" is used here to refer to the characterization of mechanical behavior of the interface when two solid bodies are in contact and subjected to relative motion. Problems in contact mechanics are often nonlinear and can involve slip/stick motion, an expanding contact area, temporary separation of the surfaces, plastic deformation, microslip, etc. Solutions of these problems result in the prediction of the stresses on the interface as a function of the externally applied loads or motions.

There are two important physical applications of contact mechanics in gas turbines:

1. Fatigue crack initiation in which the failure originates at or very near the contacting surfaces. The crack initiation may be either low or high cycle fatigue or a combination of the two. A characterization of the mechanical state of the interface (stresses and strains) is considered essential if a rational model of fatigue is to be developed.
2. The prediction of dynamic response. Under dynamic loading (that in gas turbines is often periodic) the contacting surfaces provide "stiffness" as well as damping. Friction damping is the primary source of energy dissipation in many gas turbine components. Consequently, contact mechanics affect the frequencies of peak response as well as the amplitude of response that is achieved at those frequencies. The damping and stiffness are nonlinear functions of the amplitudes, depend on the direction of the loading and the mode of vibration, and may be affected by wear, corrosion, etc.

In the case of high cycle fatigue caused by excessive vibration these two problems are usually interrelated. For example, if the area of the contacting surfaces is relatively large then only part of the interface may slip. Yet, this microslip may be the principal source of damping in the system. Predicting microslip requires a detailed knowledge of the stress distribution on the interface and how it changes during a cycle of vibration. Conversely, to develop an accurate local model of the interface requires knowing the boundary conditions that should be applied to the local model. These boundary conditions are determined by the mode of vibration.

Goals

The view of the workshop organizers is that this area of research is sufficiently difficult that we need a coordinated, global research initiative if we want to make significant progress in this critical area. The objective of the workshop is to develop a blueprint for the initiative. The specific goals of the workshop will be to:

1. Establish the state-of-the-art.
2. Determine what improvements are needed.
3. Develop a coordinated plan for achieving the needed improvements.

Appendix 1: Announcement

Sponsors

This workshop is sponsored by the US Air Force (The Air Force Office of Scientific Research) and the US Navy (NAVAIR).

Location & Dates

New Orleans, La., 3-4 June 2001

The workshop will be held in conjunction with the ASME International Gas Turbine Expo and Technical Congress in New Orleans, LA. (A website for the conference is http://www.asme.org/igti/) In order to eliminate conflict with the technical sessions at the Gas Turbine Conference, the Workshop will be held on Sunday and Monday, 3-4 June, 2001. The workshop will take place at the Wyndham Riverfront Hotel, which is next to the Convention Center (http://www.wyndham.com/Riverfront/default.cfm).

Meeting Location/Times:
Wyndham Riverfront Hotel
Sunday 3 June, 12 noon to 6:30 pm, Dinner 8:00 pm
Monday 4 June, 8:00 am to 5:00 pm, Breakfast and Lunch

Fees

No fee will be charged for participating in the workshop.

To Participate

Participation will be limited to approximately fifty people. If you are interested in attending the workshop please contact one of the organizers listed below.

Organizers

The Workshop is being organized by:

Professor Jerry H. Griffin, jg9h@andrew.cmu.edu, Carnegie Mellon University, Pittsburgh, PA, USA (phone: 412 268-3860)

Professor David J Ewins, d.ewins@ic.ac.uk, Centre of Vibration Engineering, Imperial College of Science Technology and Medicine, London, GB (phone: +44 207 594 7068).

Appendix 2: List of Participants

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